

Foundation Treatments for Dams



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PREFACE

We dam engineers are sometimes anxious to know about which way is adopted for dam engineering in foreign countries when we conflict with some difficult problems or are suspicious about usual procedures of dam engineering in our country. But it is often difficult to get answers instantly due to the difference of languages.

This may be also the same for foreign engineers, especially engineers of developing countries, and they want to know Japanese ways of designing and constructing dams. There are, however, very few books or reports written in English, dealing with general informations about Japanese way of dam engineering.

In such background this is written in English, having a purpose to provide foreign engineers with general way of foundation treatments for dams in Japan.

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C O N T E N T S

PREFACE

	Page
1. GENERAL	1
1.1 Purpose of Foundation Treatment	1
1.2 Type of Foundation Treatment Methods	2
2. FOUNDATION GROUTING	3
2.1 Purpose and Type of Foundation Grouting	3
2.2 Grouting Plan	4
2.2.1 Geological Survey	4
2.2.2 Permeability Survey (Lugeon Test)	5
2.2.3 Grouting Test	11
2.3 Equipment and Material Required for Foundation Grouting ...	14
2.4 Foundation Grouting	16
2.4.1 Injection Sequence and Precautions	16
2.4.2 Injection Pressure and Grout Mixture	18
2.4.3 Curtain Grouting	22
2.4.4 Consolidation Grouting	25
2.4.5 Blanket Grouting	26
3. SPECIAL FOUNDATION TREATMENT METHODS	29
3.1 Concrete Replacement of Brittle Zones	29
3.2 Cut-off Plug and Continuous Cut-off Wall Bars	31
3.3 Bedrock PS Method using Steel Bars	32

1. GENERAL

1.1 Purpose of Foundation Treatment

Since natural bedrock is used for the dam foundation, the foundation treatment is necessary to prevent reservoir drainage by the permeability or the unequal settlement of the dam. In the worst case, an enlarged leakage path may cause piping which, in turn, will cause the dam body to be washed away (Example, Teton Dam) or to start sliding (Example, St. Francis Dam), leading ultimately to great disasters.

All of these occur due to the characteristics of natural bedrock, scarred surfaces, such as crevices or fault fractured zones, which distinguishes the bedrock from ordinary rocks.

This is why the dam foundation requires artificial treatments. The procedure for improving bedrock is generally called the foundation treatment. The degree of the foundation treatment differs naturally by the load conditions for the foundation rock. The difference of load conditions may be assumed to arise from the type of dam and the dam height. The discrepancies in natural bedrock used for the dam foundation can be summarized as - - -

1. permeability;
2. deformability;
3. strength;

Permeability is not a critical factor in relation to the type of dam or its height among them. Deformability generally presents more serious problems for concrete dams than for fill dams; therefore, an appropriate minimum treatment must be executed to keep the deformation small. Strength of the foundation rock almost poses no problems in the case of fill dams since it has sufficient strength per unit area.

In the case of concrete dams, strength presents a problem. More strength is required for the foundation rock according to the height or type of dam, for instance, an arch dam requires a stronger founda-

tion rock than a gravity dam. When selecting the dam site, it is very important to choose a more applicable location where the dam foundations satisfy the above-mentioned conditions.

1.2 Type of Foundation Treatment Methods

Foundation treatment methods are broadly divided into two types: one is foundation grouting, and another is a special foundation treatment mainly composed of a concrete replacement work.

There are four types of foundation groutings.

1. Curtain grouting
2. Consolidation grouting
3. Blanket grouting
4. Other types

Special foundation treatments are broadly divided into -- --

1. concrete replacement of brittle zones such as fault fractured zones;
2. water stoppage by a continuous cut-off wall;
3. steel bedrock binding to control the bedrock deformation.

These methods are explained in detail in the following chapters.

2. FOUNDATION GROUTING

2.1 Purpose and Type of Foundation Grouting

The bedrock in its natural state has, as previously mentioned, many scarred surfaces such as, fissures, etc. These fissures provide paths for the infiltration of water and cause plastic deformation under loads.

Thus the grouting means to fill the fissures with hardened cement by injecting a cement milk. The grouting is classified as follows:

(1) Curtain grouting

This grouting is provided down to a comparatively deep depth at the foundation of either upstream sections of a concrete dam, or the impermeable wall core of a fill dam to check water seepage from the reservoir through the foundation rock.

(2) Consolidation grouting

This grouting is provided at a comparatively shallow depth over the entire area of the dike base to reduce, as much as possible, the plastic deformation at the concrete dam foundation near the ground surface.

(3) Blanket grouting

This grouting is provided at a comparatively shallow depth to form cover rock to check unequal deformation at the foundation of the impermeable wall core and water seepage to make curtain grouting easily.

(4) Other types

(For example, contact grouting formed near the interface between concrete dam and the foundation having a steep slope.)

For a concrete dam, curtain and consolidation grouting are used, while curtain and blanket grouting are used for a fill dam.

Concrete Gravity Dam

Arch Dam

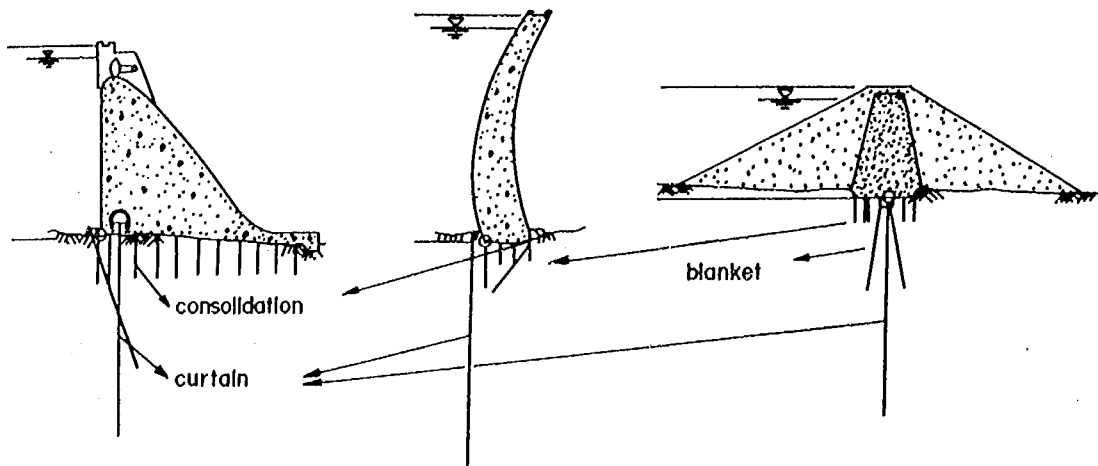


Fig. 1 Type of foundation grouting

2.2 Grouting Plan

Before grouting, a plan should be devised to determine the scale of grouting to be carried out. In order to draw up an adequate grouting plan, it is necessary to conduct a survey and write the results based on the following:

- a) Conduct a thorough survey to determine the nature of the foundation rock. (For this, the complete investigations concerning a geological survey, permeability and deformability about the foundation rock should be conducted.)
- b) Set up a target related to the scale of improvement to be made.
- c) Decide on the details of grouting to obtain the required target by grouting tests.

2.2.1 Geological Survey

When drawing up the grouting plan, it is necessary to keep in mind geological characteristics and other areas which require special attention. The scale of the grouting can be determined to a certain extent by this.

An example of a typical geological section for special attention is shown in Figure 2.

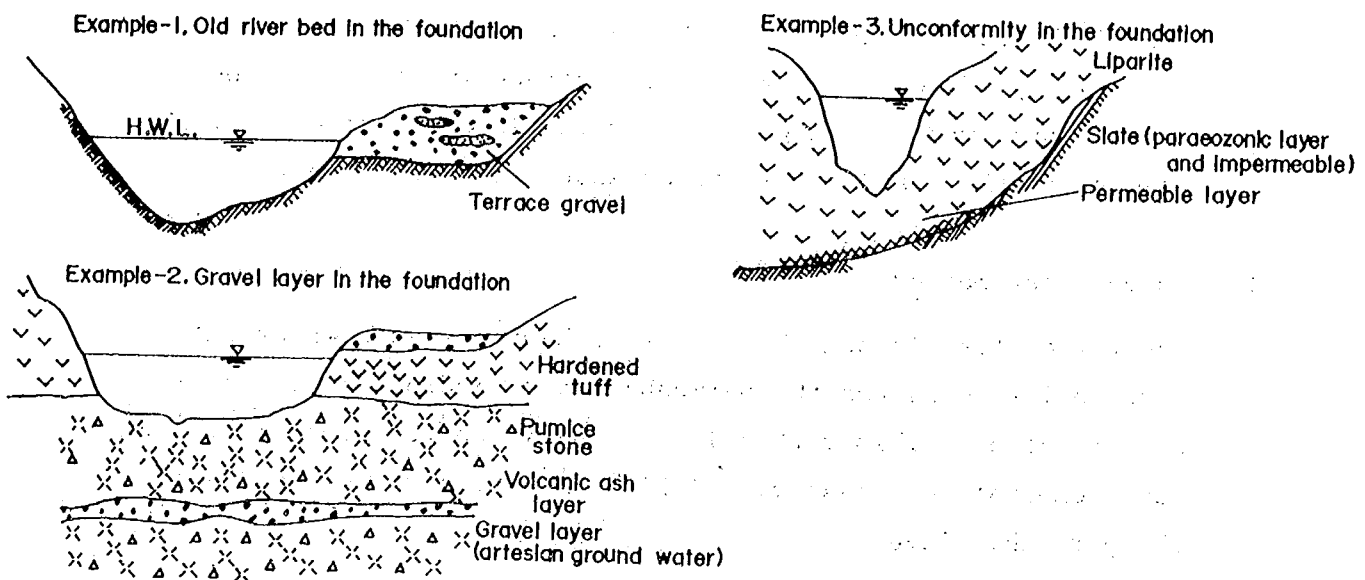


Fig. 2 Example of a typical geologic section for reference

In addition, it is quite natural that each item comprising the geological map will be used as reference data when drawing up the grouting plan.

2.2.2 Permeability Survey (Lugeon Test)

When drawing up the grouting plan, the permeability of the foundation rock must be known. This is done by a permeability test. In Japan, the Lugeon test is employed as the permeability test for the bedrock. The test method and items requiring special attention are explained next in detail.

a) Position and scope of the Lugeon test

The Lugeon test must be done at the riverbed and on both right and left banks in the area where the grout curtain is to be placed; down to about one-half the maximum

height of the dam, or where geological

problems are present down to almost

the maximum height of the dam

(Figure 3).

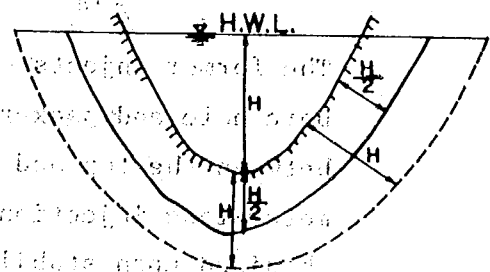


Fig. 3 Scope of Lugeon Test

This is because of the high water pressure at the riverbed and the possibility of loosened, weathered bedrock in upper sections. Furthermore, where a large Lugeon value is encountered near the planned depth, testing must be extended further downward.

b) Lugeon test method

The Lugeon test is done by injecting high-pressure water into bored holes to assess the permeability of bedrock by its degree of permeation. This method is generally adopted since it can be done comparatively easily, quickly and we can roughly estimate the permeable layer.

The Lugeon test is divided into: a single packer method, and a double packer method. The equipment used and the difference in respective injection methods are as shown in Figure 4.

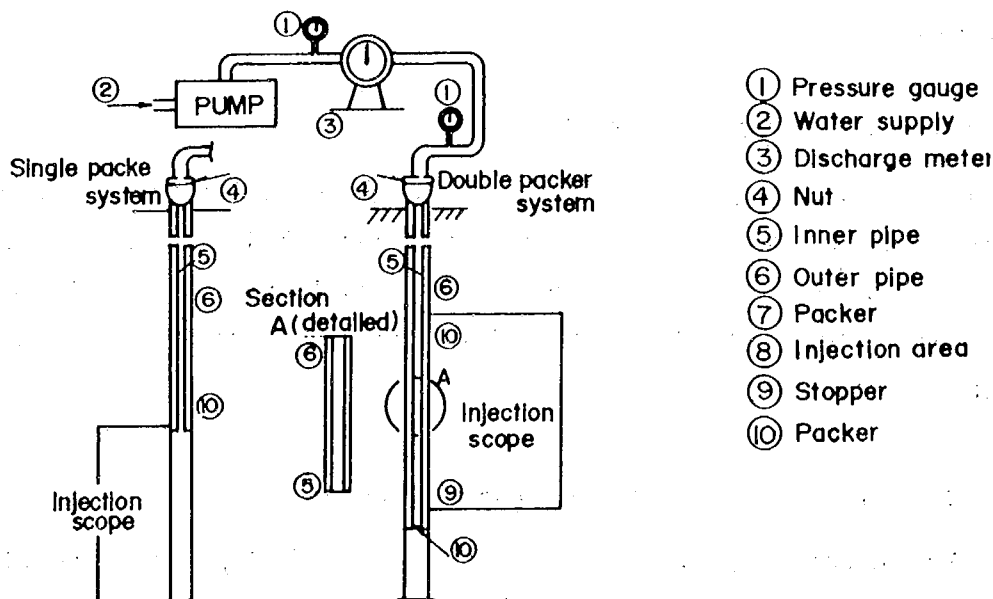


Fig. 4 Lugeon test equipment

The former injects water from the location between the bottom of the bore hole and packer, while the latter injects water from section A between the top and bottom packers. Both methods often adopt 5 meter-long injection impressing sections, and the Lugeon value is obtained upon stabilization of the injection quantity under the pressure of 10 kg/cm^2 for a bore hole per meter.

We called 1 Lugeon when 1 ℓ /min water was injected into a bored hole per meter under the pressure of 10 kg/cm². Although the single packer method process is complicated since it requires boring for each test, error from water leakage at the packer is little due to a reduced number in required packers. The double packer method process is less complicated since the total length of the bore hole is proposed before hand, but reliability poses a problem and there are possibilities of increased water leakage. Consequently, this method is rarely used when the main purpose is for survey.

The following items require special attention when the Lugeon test is done.

- (1) To check for water leakage from the packer, set the packer very carefully. In addition, the cause of an excessive injection quantity is often due to a bad packer or improper adjustment. Replace the packer, reset, or change the position in such a case.
- (2) When the injection quantity exceeds the discharge quantity of the pump and pressure does not increase, either change to a larger capacity pump or shorten the stage length.
- (3) Before starting the test, allow ample time for the injection quantity to stabilize.
- (4) Indicate clearly whether a ground-water table exists. If it exists, record the location, if there is spring water, its quantity and pressure, and conditions such as boring hole diameter, gauge position, etc. under which the test was executed.
- (5) Setting a packer at a fault section is difficult, and at the spot where cement was laid, the Lugeon value does not indicate a correct value. These conditions should also be indicated clearly.

When the Lugeon value per stage of each bore hole is obtained, enter this in the dam site section to draw up the Lugeon map (Figure 5).

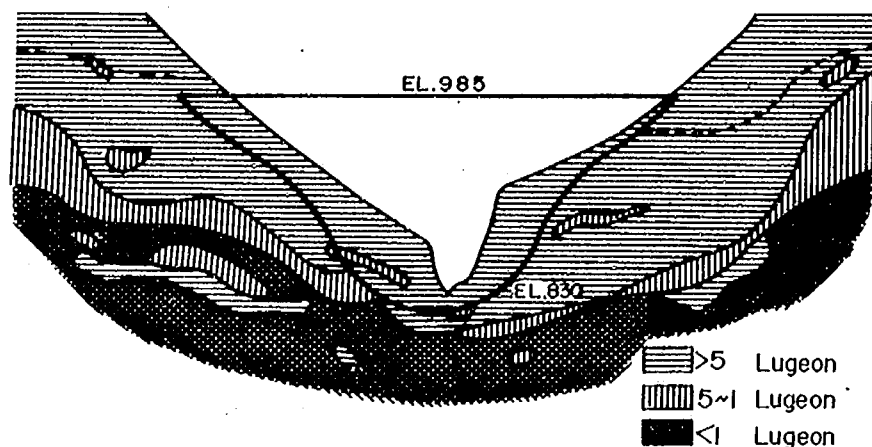


Fig. 5 Lugeon map of foundation bedrock it Nagawawatari Dam

c) Lugeon test disadvantages

- (1) There are no uniform standards covering bore holes, gauge positions, stage lengths, etc.
- (2) Boundary conditions such as, the groundwater level, are not clearly defined.
- (3) There is no specific reason to set the injection pressure at 10 kg/cm^2 .

However, the Lugeon test is widely used; because of comparative simplicity in testing, the availability of practical knowledge on the degree of permeation of bedrock, and because of the ease in obtaining the data for grouting since water is directly impressed into the bore hole.

Furthermore, although there are problems yet to be revolved to link directly the actual surveyed Lugeon value with the permeability value coefficient defined by Darcy's formula where irregular crevices and voids are in the bedrock, however the following formula is used to set up a standard.

$$K = \frac{Q}{4h} \cdot \frac{\ln \left(\frac{2\ell}{\phi} \right)}{2\pi\ell} \dots\dots\dots (1)$$

where: Q = Injection quantity (cm³/sec)

h = Water head (cm)

ℓ = Length of test section (cm)

φ = Bore hole diameter (cm)

According to this formula, with a bore hole of 40 to 80 millimeters in diameter, 1 Lugeon equals about 10⁻⁵ cm/second.

d) Injection pressure

When using the Lugeon test for good bedrock with an injection pressure within 10 to 15 kg/cm³, it is known that injection pressure and injection quantity Q are in proportion as shown

by line "a" in Figure 6. When the injection pressure is further increased; P and Q are no longer in proportion beyond a certain pressure amount and Q rapidly increases.

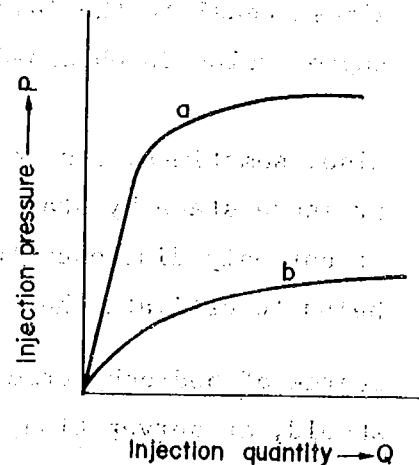


Fig. 6. Relationship between injection pressure and injection quantity

Meanwhile, at the bedrock where weathering has considerably advanced, P and Q are not in proportion even within the above-mentioned pressure range, and the tendency as shown by line "b" in Figure 6. appears from the beginning. When an injection pressure of 10 kg/cm² cannot be employed, it is general practice to obtain the Lugeon value by proportional conversion of the injection pressure. The converted Lugeon value is obtained from the following formula:

$$Lu = \frac{10Q}{P\ell} \dots\dots\dots (2)$$

where: Lu = Lugeon value

Q = Injection quantity (ℓ/min)

P = Injection pressure (kg/cm²)

ℓ = Length of test section (m)

When strong injection pressure is used for bedrock where weathering has advanced, there is danger in causing the harmful displacement of the foundation rock. Consequently the test must be executed with a pressure of less than 10 kg/cm². In this case, it must be noted that since P and Q are not in proportion as mentioned above, the converted Lugeon value will be smaller than the actual surveyed Lugeon value.

Testing is frequently done for curtain grouting, etc. when the bedrock is in good condition; higher than 10 kg/cm² which is almost equal to the injection pressure. In this case, a larger Lugeon value is obtained.

Also, sometimes, testing is done by changing the injection pressure stage by stage, which is regarded as important since it not only discloses the degree of bedrock permeation, but also helps to estimate the extent of a possible improvement in the degree of bedrock permeation. In addition, the injection pressure should, at survey time, be adjusted in consideration of the hydrostatic head and pipeline friction down to the middle point of the test stage.

e) Determining results of the Lugeon test

For results of the Lugeon test, various criteria become available to enable the grouting plan to be drawn up. These are given below.

- (1) The range for grouting becomes clearly defined,

- (2) The scattered presence of permeable layers becomes clear.
- (3) The location of bedrock suitable for the foundation rock can be determined. (The foundation rock as viewed from the cut-off wall of the fill dam and from impermeability of the concrete dam.)

The range for improvements through grouting can be determined by whether it has a suitable degree of impermeation for foundation rock. In Japan, as a standard for the suitable degree of impermeation, it is set at 1 to 2 Lugeons for the concrete dam and 2 to 5 Lugeons for the fill dam. Therefore, by drawing a Lugeon map, the required grouting range can be clearly defined. If there is a scattered permeable layer as shown in Figure 2, it will always be detected.

One of the important uses of the Lugeon test is to find the suitable site for a rock-contact surface of the cut-off wall for the fill dam by paying attention to permeability. It is generally known through experience that considerable technical hardships are accompanied when attempting to improve a section of 20 Lugeons down to 1 to 3 Lugeons through grouting, and unless an enormous loss is involved, the bedrock with a high degree of permeation (over 20 Lugeons) is generally excavated for removal.

2.2.3 Grouting Test

In Japan the desired Lugeon value for improvement through grouting is set, by the dam type, at 1 to 2 Lugeons for concrete dams and 2 to 5 Lugeons for rock-fill dams. There is no specific reason for the difference in Lugeon values by dam type, and for the rock-fill dam, it is often constructed in a comparatively bad condition site because of more lenient strength conditions required for the foundation rock. When the above desired Lugeon values are chosen, it can be interpreted to indicate the possible value of improvement that can be obtained without hardships even on such rockbeds. Consequently, even with a fill dam, if it is designed for a rockbed that

can be easily improved to 1 to 2 Lugeons, improvements should be made.

Now, it is necessary to know, before starting the main construction, the density and injection specifications of grouting which make it possible to obtain the above-mentioned desired Lugeon values for improvements. To obtain this, a grouting test is done during the survey stage.

The grouting test is often done with the purpose of clarifying the following points:

- (1) Outlook for improvements through grouting
- (2) Grout hole spacing and pattern selection
- (3) Determining the injection pressure
- (4) Determining the test standards and collection of estimation materials

As an example of a grouting test, the Misokawa Dam (rockfill dam: $H = 135$ m) is illustrated. The grouting test was done on sand stone and slate comprising the dam site rock base.

The test was conducted by injecting square patterns as shown in Figure 6 in the order indicated. By obtaining the Lugeon value and cement injection quantity for each hole, the improvement degree for the permeability of bedrock was determined when the grout holes were spaced more closely. (See Figure 6.)

Next, came the injection specifications. Generally, it is common for injection specifications to call for changing the mixture according to initial Lugeon values since cement milk due to its viscosity, does not enter smaller cracks smoothly when the density is higher. Also, the maximum injection pressure is often determined according to the initial stress around the bedrock to be subjected to injection. It is an absolute prerequisite that the bedrock not be lifted.

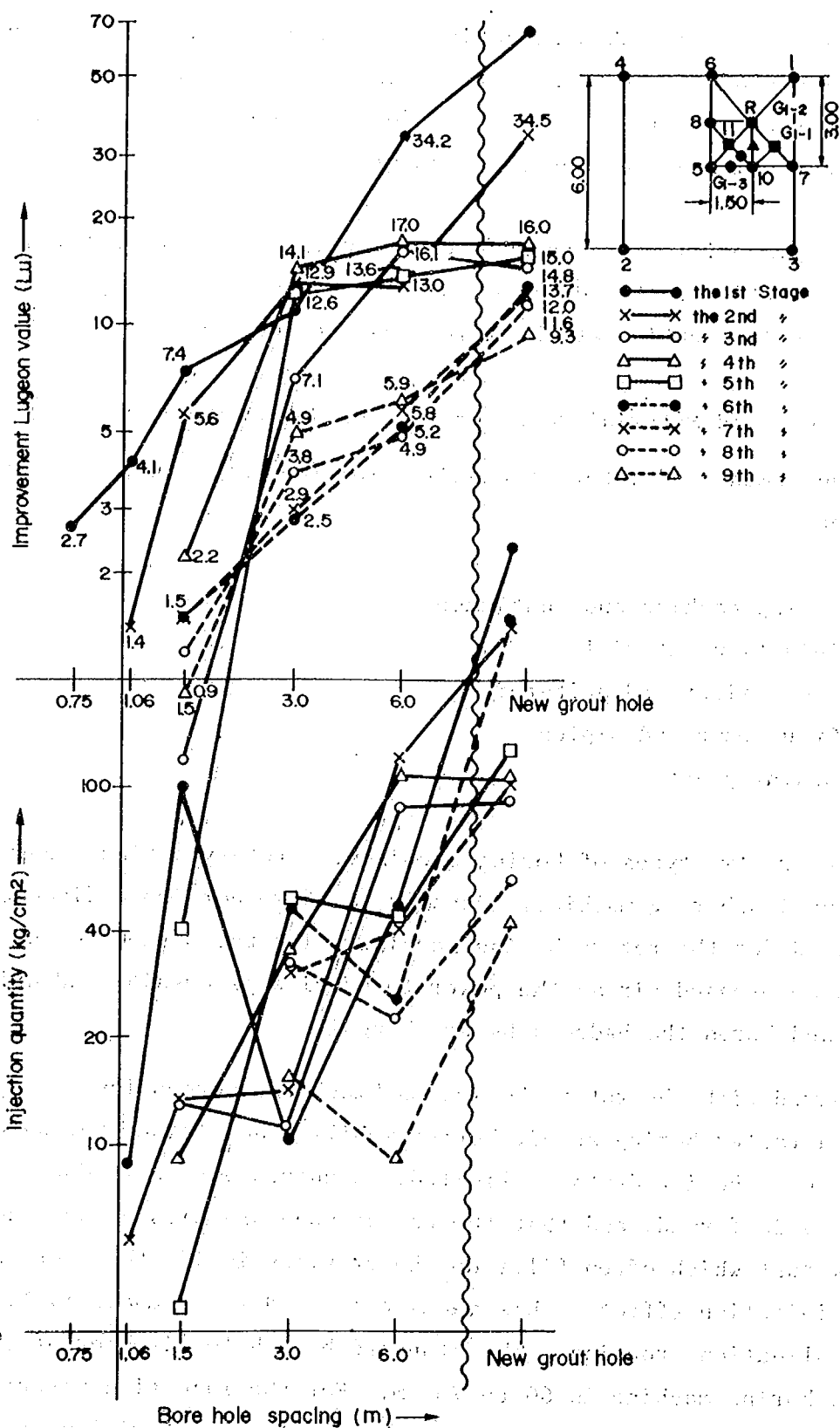


Fig. 7 Lugeon value and injection quantity by stages in relation to bore hole spacing (Misogawa Dam, Sand Stone)

It is important, when executing a grouting test, to check the critical pressure of the bedrock, relationships between grout density and total injection quantity, etc., to render the materials to determine injection specifications for the main grouting.

Thus, materials for the main grouting are collected entirely through the grouting test and the completion of the detailed plan enables a rational execution of the main construction work.

2.3 Equipment and Material Required for Foundation Grouting

The equipment and material required for foundation grouting are as follows:

- a) Boring machine and instrument
- b) Injection material
- c) Grout mixer and agitator
- d) Grout pump and piping
- e) Mixing plant

There are two types of boring machines, a rotary boring machine, and percussion boring machine. Usually, a 46 mm bore hole diameter is adopted for the rotary boring machine. The percussion boring machine uses compressed air as the power to provide percussion and drive the bit and bores the bedrock by crushing it.

Compared with the rotary boring machine, the percussion boring machine has a faster boring speed, better mobility and lesser boring cost, etc. However a boring depth is limited, an uneven bore wall due to percussion boring is formed, and that the use of non-core bits produce a lot of rock dust which often fills up the crevices inside the bedrock, lowering the injection effect. This machine is used for comparatively shallow consolidation grouting. The standard bore hole diameter of the percussion boring machine is 60 to 75 mm. For the injection material, cement is used, but in order to fill up the crevices, material must have the following characteristics:

- (1) The injection material must be fine-grained.
- (2) The grout particle must disperse evenly without the excessive

bleeding and have a good liquid texture.

(3) The material, after hardening, must have the required strength.

In particular particules must be very fine-grained when the crevices are narrow. For this, either bentonite is mixed with the cement or the colloid-cement is sometimes used.

Use a grout mixer that mixes the cement, water, and other additions evenly. The agitator is used to prevent separation of grout materials.

There are two types of grouting, namely a rated discharge type grouting pump and a discharge adjustment type grouting pump. The discharge adjustment type grouting pump, however, controls pressure and injection quantities and lately is being widely used.

The piping method for the injection pipe shown in Figure 8 is used.

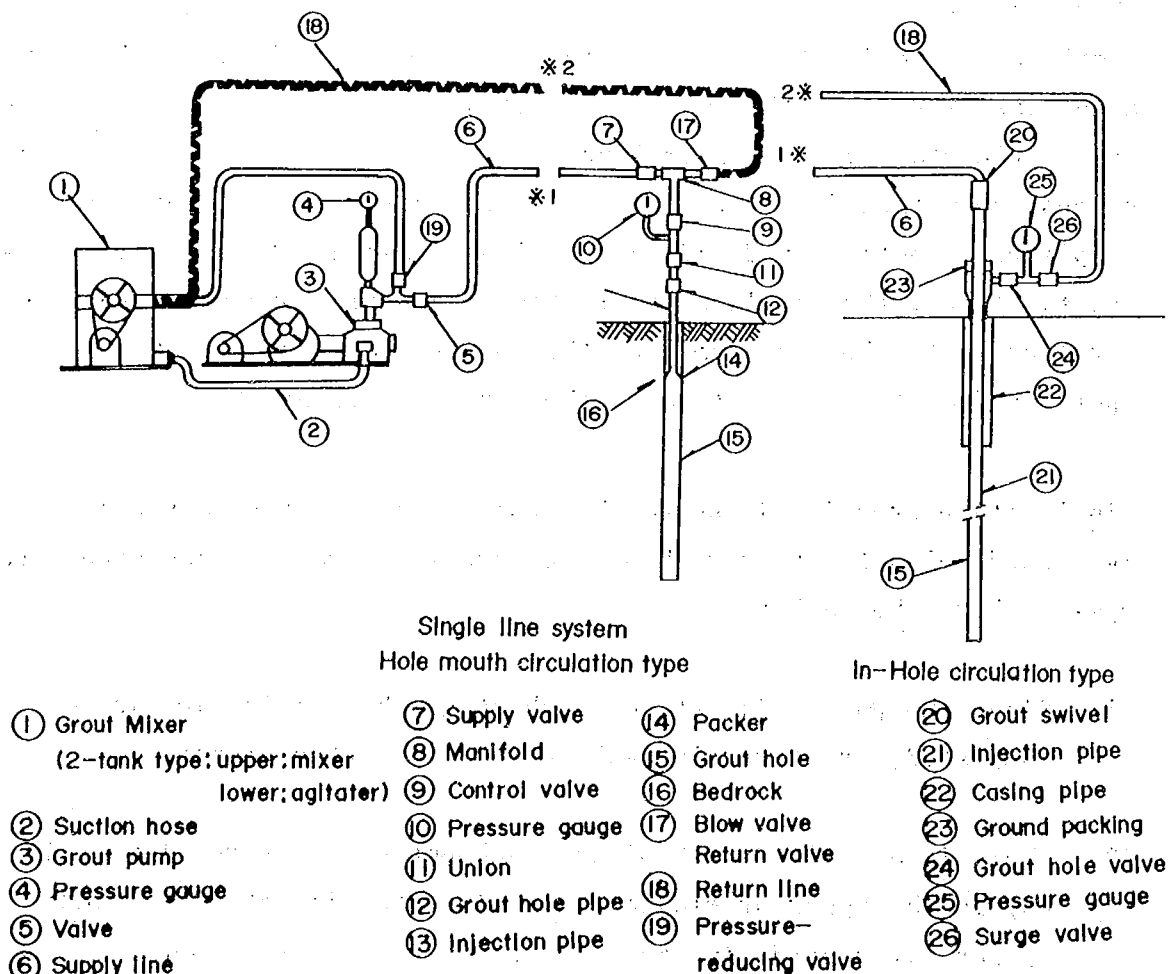


Fig. 8 Grouting piping

2.4 Foundation Grouting

2.4.1 Injection Sequence and Precautions

The injection work is done according to the following sequence:

- (1) Washing
- (2) Pressure test
- (3) Injection

The purpose of washing is to wash away the rock dust which adhered or accumulated inside the bore hole at the time of boring. Pressure test is done before injection to check the permeability of the bedrock—required in determining the grout blending, a stage length, injection quantity per unit hour, and the injection pressure. Upon completion of these preparations, the actual injection begins.

There are two kinds of injection methods; a one stage method which completes injection to the scheduled depth by a single injection, and a successive stage method which completes injection in several stages. The single stage method is employed for shallow bores and the successive-stage method for deep bores. Successive-stage grouting which completes injection by dividing the planned depth into several stages, has two types; the single stage routing type which operates from the bore top to the bore bottom, and the packer grouting type which operates from the bore bottom to the bore top (Figure 9).

Single stage grouting is suited because of the relative advantages mentioned below for poor rock or when crevices are full and grout leaks upward above the packer.

- (1) Since the packer is set for each stage where injection is completed, grout rarely leaks upward above the packer.
- (2) There is a smaller risk of encroachment by fractured layer, if any in the upper or middle zone, since the injection proceeds deeper after hardening the fractured layer, with grout.

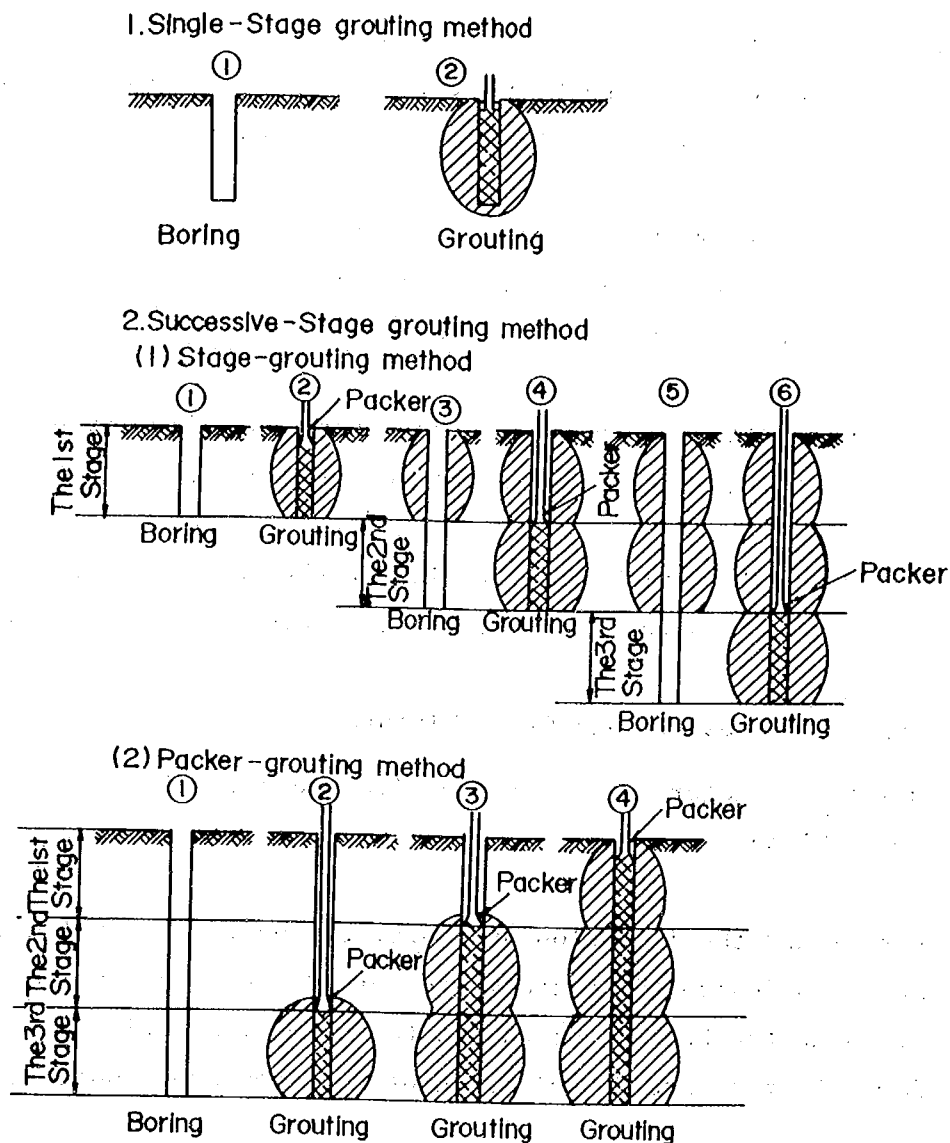


Fig. 9 Explanation on grouting methods

(3) Since additional borings are required for hardened grouts the construction cost increases.

(4) Since a boring is suspended during the injection a longer construction period is required.

A packer grouting injects a grout after the boring is completed for the full scheduled depth, from the lower stage to upper stage in order.

Packer grouting is suited because of the relative advantages mentioned below for the grouting bedrock where there are comparatively few crevices; whereby a grout does not leak upward above the packer.

- (1) Once after the boring machine is installed, it is possible to bore continuously until reaching the scheduled depth, thus shortening the construction period.
- (2) Once after the packer is inserted, only lifting by the stage remains, which reduces the need for human labor.
- (3) There is a risk that lifting of the packer is impossible in the bedrock where the grout leaks upward above the packer.

2.4.2 Injection Pressure and Grout Mixture

Important factors at injection time are the injection pressure and the grout blending.

The higher the injection pressure, the easier injection becomes since crevices inside the bedrock are spread out. On the other hand, it lifts up the bedrock or causes the harmful plastic deformation to the dam. So the careful selection of the pressure amount is required.

Usually, the maximum injection pressure is determined by experiences, according to the followings.

- (1) The injection pressure is determined according to the bedrock state covering and superstructures. Also, a higher pressure is employed when the bedrock state is a big lump rather than a horizontal layer, or the injection pressure is increased according to the grouting sequence: pressure is increased by each stage proceeding from the first bores, the second bores, and the bores. When the grout density to be injected is high, a higher pressure is employed than when the density is low.

- (2) In the grouting test done before an injection, the proportion range between the pressure and permeation quantity, that is, the limitation pressure is obtained, and based on it the maximum limitation pressure is determined.

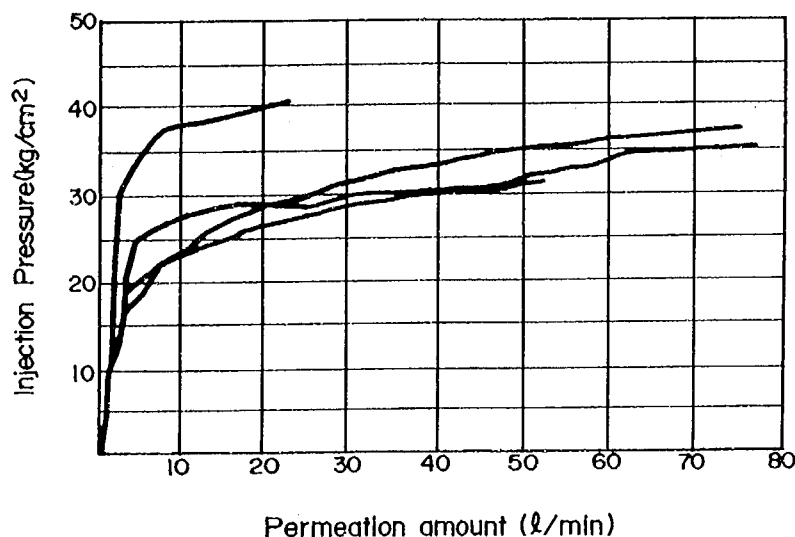


Fig. 10 Example of injection pressure - permeation amount
(curtain grouting)

As mentioned above, on the basis of the stability of the bedrock, a ground density, grouting test results, etc, the injection pressure is determined according to the depth from the ground surface, although it may not be determined uniformly.

For the bedrock covering d (m), the injection pressure P (kg/cm^2) of 0.4 to $0.6 d$ by consolidation grouting and 0.5 to $1.0 d$ by curtain grouting are given as maximum injection pressure standard values for a high dam to be constructed on the good bedrock.

In medium - and smaller - sized dams that have been built in Japan in recent years, each foundation rock is not generally good, and each bedrock covering is mostly less than 0.25 to $0.4 d$. These values however, are considerably larger than the $0.23 d$, which is used by the U.S. Development Authority as the guidance value. In sum, it is recommended that the injection pressure is determined

on the basis of grouting test results while being guided by such past experiences as cited above.

Mixture proportion must be determined according to an injection purpose and conditions of the bedrock, and also be changed according to the injection state.

What is important to a grout density is that the viscosity increases in proportion to the density. Therefore, less sticky grout is more easily injected because of its small viscosity, but it takes more time for the injection of an identical quantity of cement than the denser grout. It also is generally accepted that it may possible result in a decrease of grout strength following its solidification when sufficient pressure cannot be applied.

The cement grout mixture of water and cement is usually within the weight proportion of 10 to 1 ($W/C = 10 \sim 1$). For particularly large crevices the W/C proportion of 0.5 or mortar is sometimes used.

As for the mixture proportions at the beginning of injection, changing the mixture proportions, and the mixture proportions at the end of injection present themselves as problems. Concerning this, there are different ways to handle these problems depending on the condition of the bedrock in question. The Terauchi Dam (rock fill dam; H-83 m) is illustrated as follows (Table 1) as an example.

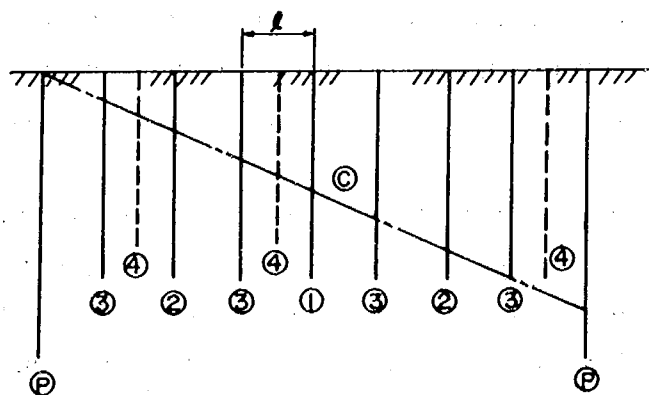


Fig. 11 Split spacing method

APPENDIX F

Table 1. Standards for changing the grout mixture proportion in Terauchi Dam

(1) Grout mixture proportion for initial injection

Based on the permeability test results the following initial mixture proportion is used.

Permeation quantity	40 l/min over/5m	40 l ~ 10 l/min	10 l/min under/5m
Mix No.	3	2	1

Mix No.	Mix used (C+B: Gravity W+P Proportion)	20 min. Injection quantity	Changed Mix C/W
1	1 : 8	700	1 : 6
2	1 : 6	600	1 : 4
3	1 : 4	500	1 : 2
4	1 : 2	400	1 : 1

(2) Changing the mixture proportion

When the injection quantity after twenty minutes exceeds the above amount, use a higher density mix gradually. Even if the injection quantity is less than indicated above, continue injection for another twenty minutes, and if no decrease in the injection quantity is observed, gradually change to a higher density mix.

(3) Injection control

Ensure that the injection quantity per minute does not exceed 10 liters/minute/m.

(4) Injection omission

During the permeation test, if the permeation amount under the rated pressure is lower than 0.1 liter/minute/m, injection can be omitted under the direction of the supervisor.

(5) Completion of injection

Injection can be regarded as completed, as a rule, when it has continued for more than twenty minutes with the permeation amount staying under 0.1 liter/minute/m under the rated pressure.

2.4.3 Curtain Grouting

As previously mentioned, curtain grouting is used to check the water seepage flow. Besides protecting the drainage of reservoir water, it is useful in reducing the uplift in a concrete dam and the infiltration flow velocity in a fill dam.

Curtain grouting is generally started from the footing of the upstream sections of a dam, inland inspection galleries or grouting galleries set up inside the bedrock.

The area of curtain grouting is determined based on the dam type and height, topographic features of the dam site, and the state of the bedrock. As already mentioned, there are many times when sections having 1 to 2 Lugeons of permeability in the case of concrete dams and about 2 to 5 Lugeons in the case of rock fill dams are designated as a target in improvement areas. Although this is quite a rational decision, there remains a problem of whether the same target of the improvement Lugeon value can be employed for high (where high water pressure is present) as well as for low dams. The following formula is used to determine the depth of the grouting area.

$$d = H/3 + C \quad \dots\dots\dots (3)$$

where: d = bore depth (m)
 H = dam height (m) above bore
 C = constant, 8 to 25 (m)

The execution sequence in curtain grouting is important and usually the split spacing method is adopted. The execution sequence is below.

(1) Pilot bore (P)

The Lugeon test and injection are done in advance by boring a depth 10 to 30% deeper than the scheduled grouting range or depth, at spacings of about 10 to 30 m, in order to learn the state of the grouting area; the suitability of the scheduled area, the execution method, etc. can then be investigated.

(2) The first bore (1)

Based on the results of (P), the first bore (1) is done.

(2) The second bore (2) - the third bore (3) Based on the results of bore (P) and the first bore (1), the second bore (2) is done and by using the results, the third bore (3) is also done.

(4) Additional bore (4)

When necessary after analyzing the total results, an additional bore (4) is done.

(5) Checking bore (C)

After a thorough consideration of the total results from bore (P) to the additional bore (4), a checking bore (C) is done at the key point to perform the Lugeon test and injection in order to determine the effects of grouting.

The effects of curtain grouting are determined by the decrease in the Lugeon value and unit quantity of cement injection at respective injection bores and by test results of checking bore, which become the factors in correcting the grouting plan.

Checking bore is very important as the final determining factor on the effects of curtain grouting and must be done.

Checking bore must be arranged so that it evenly covers the area where curtain grouting is done and must cross the grouting bores diagonally every 15 to 20 meters. The checking bore method must also be employed during actual construction work, where large Lugeon values and/or injection quantities are detected or for faults that may pose problems.

The effects of an injection are determined from the results of the Lugeon test.

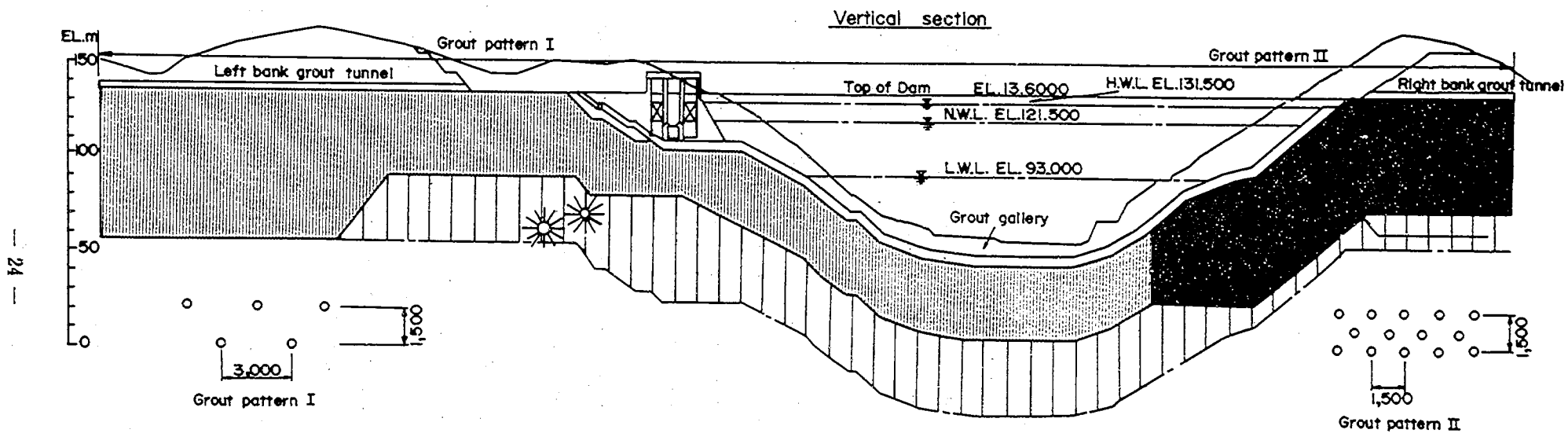


Fig. 12 Example of curtain grouting execution (Terauchi Dam)

It is recommended that the results of the Lugeon test (by checking bore) indicate that about 85 to 90% of the total number of stages have a lower Lugeon value than the target value.

An example of curtain grouting is shown in Figure 12.

2.4.4 Consolidation Grouting

Consolidation grouting mainly aims at improving the deformability of the concrete dam foundation, but is also effective in checking water seepage flow into the bedrock surface layer. Figure 13 shows how consolidation grouting was effective in improving the deformability for the Amagase Dam (arch dam; $H=72$ m).

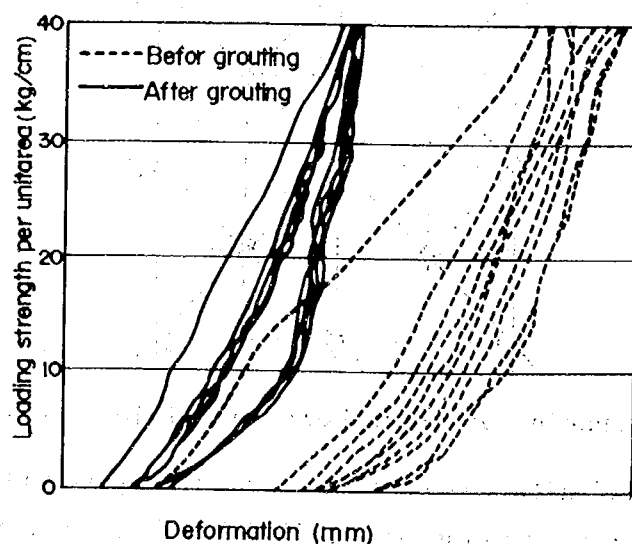


Fig. 13 Difference of deformation characteristics after consolidation grouting (Amagase Dam)

There are two ways to do consolidation grouting; one is done before pouring concrete and the other is done when concrete placement reaches a predetermined height. Although the latter costs more and is not advisable from the viewpoint of actual construction work, it is effective in providing excellent grouting as the injection pressure can be increased and there is no possible chance of the grout leakage. Either of the above ways is adopted depending on the state of the bedrock and the latter is commonly adopted where the bedrock condition is not so good.

Consolidation grouting is usually provided for the overall surface of the arch dam foundation and is more tightly impressed into areas where working stress is high, or where bedrock conditions are unstable. Also, for the arch dam, it is usually done deeper than for a gravity dam. For the gravity dam, consolidation grouting is concentrated on areas where working stress is high or where the bedrock conditions are unstable and is not necessarily done for the overall surface of the foundation.

Consolidation grouting is done to the depth of about 5 to 10 meters and bore holes are spaced at intervals of 2.5 to 5.0 meters. Spacing of bore holes and the sequence of execution are shown in Figure 14.

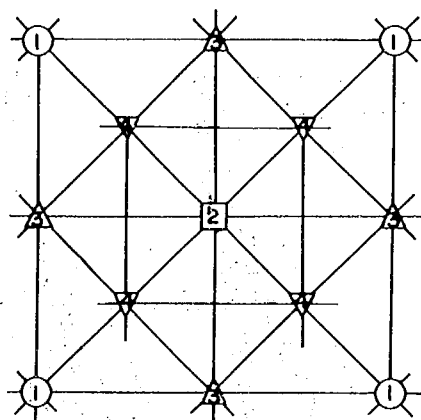


Fig. 14 Spacing of grout holes and injection sequence

There is no definite Lugeon value as an improvement target in the case of consolidation grouting and additional boring depends on the Lugeon values and the decrease in injection quantities and the determination is left to the chief engineer's own discretion.

2.4.5 Blanket Grouting

Originally, blanket grouting was arranged radially from both sides of the curtain grouting as reinforcement. Lately; however, blanket grouting in Japan is frequently done for the overall area of the cut-off wall to check water seepage flow into the surface layer.

In such a case, the same spacing rules apply as in consolidation grouting, that is, the bore holes should be placed closer near curtain grouting and spaced further near the filter sections. An example of the Iwaya Dam (rock fill dam, H=127.5 m) is shown in Figure 15.

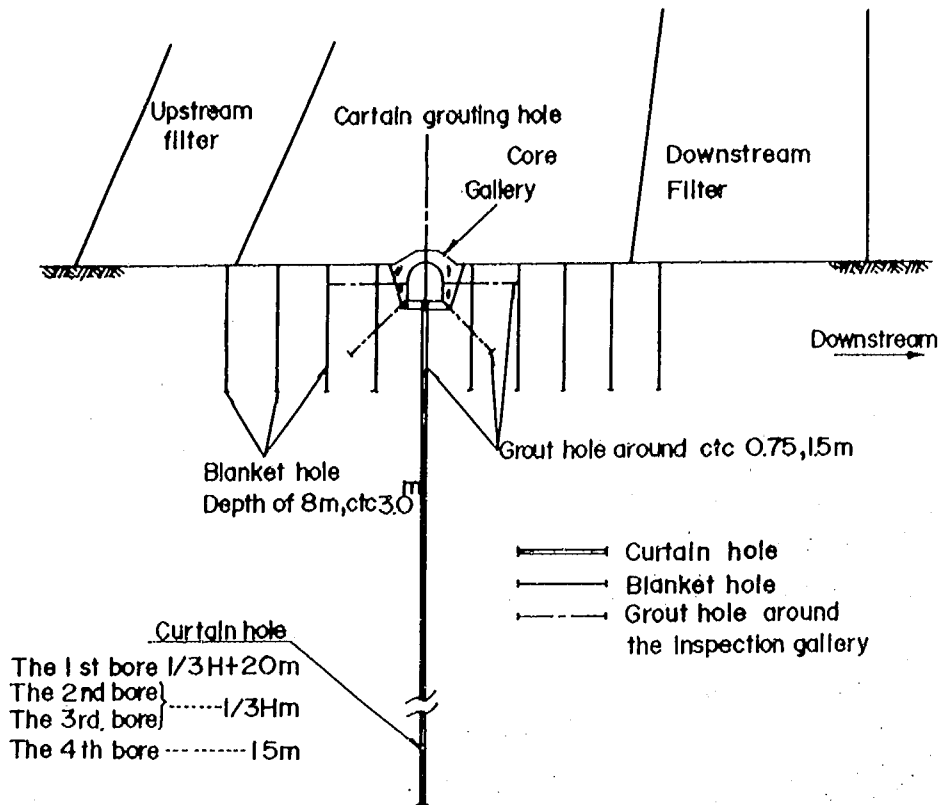


Fig. 15 Example of blanket grouting (Iwaya Dam)

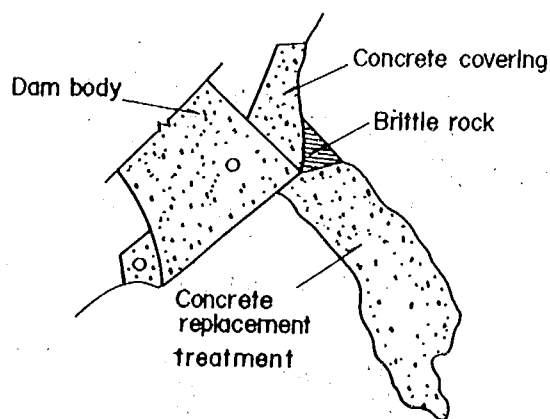
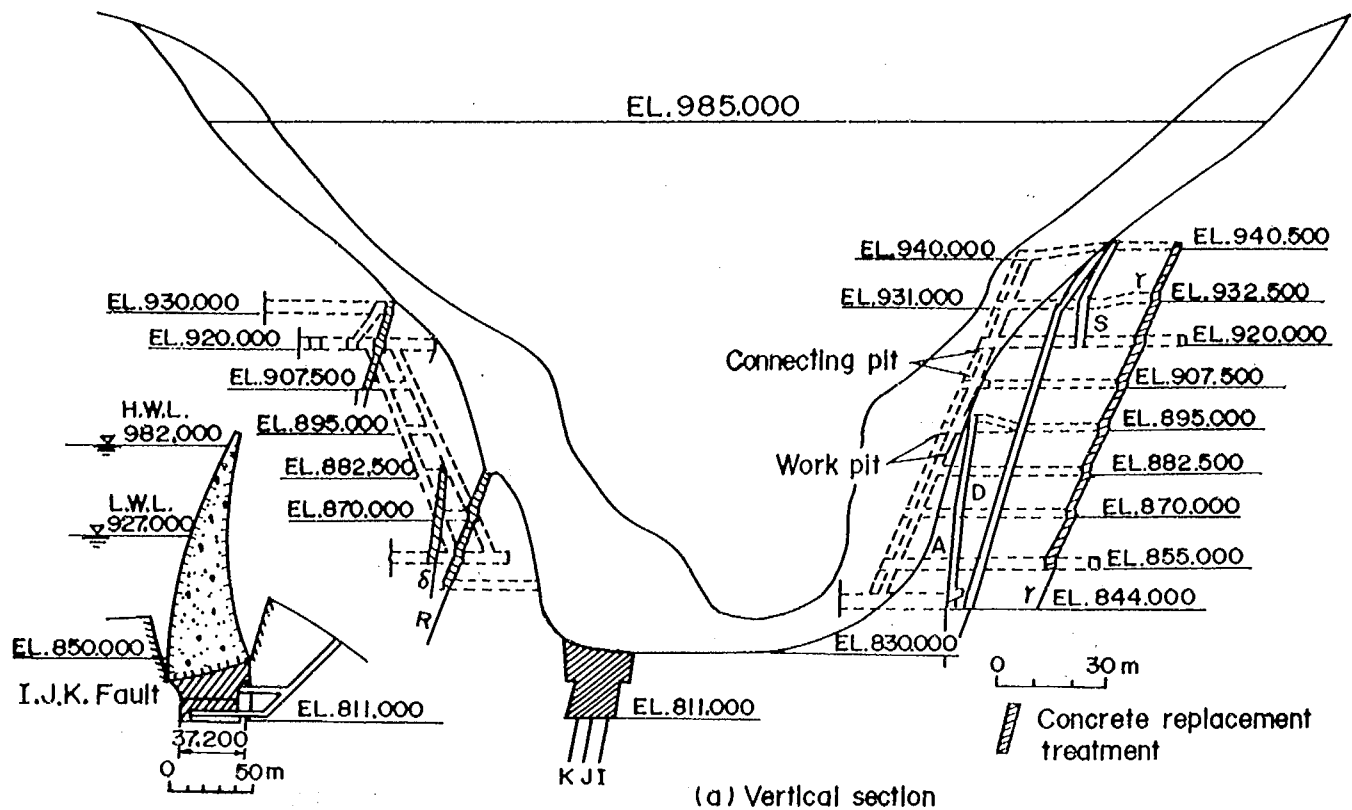


Fig. 16 Concrete replacement treatment at Kurobe IV Dam

(2) Replacement of faults at the Nagawado Dam

As the collapse of the Malpasset Dam indicated, the landslide along the brittle zone always presents a problem. At the Nagawado Dam (arch, $H=155$ m), an almost vertical fault line running in an up and downstream direction was detected, and a large-scale replacement of the fault was done as shown in Figure 17.



(c) I.J.K. Fault treatment

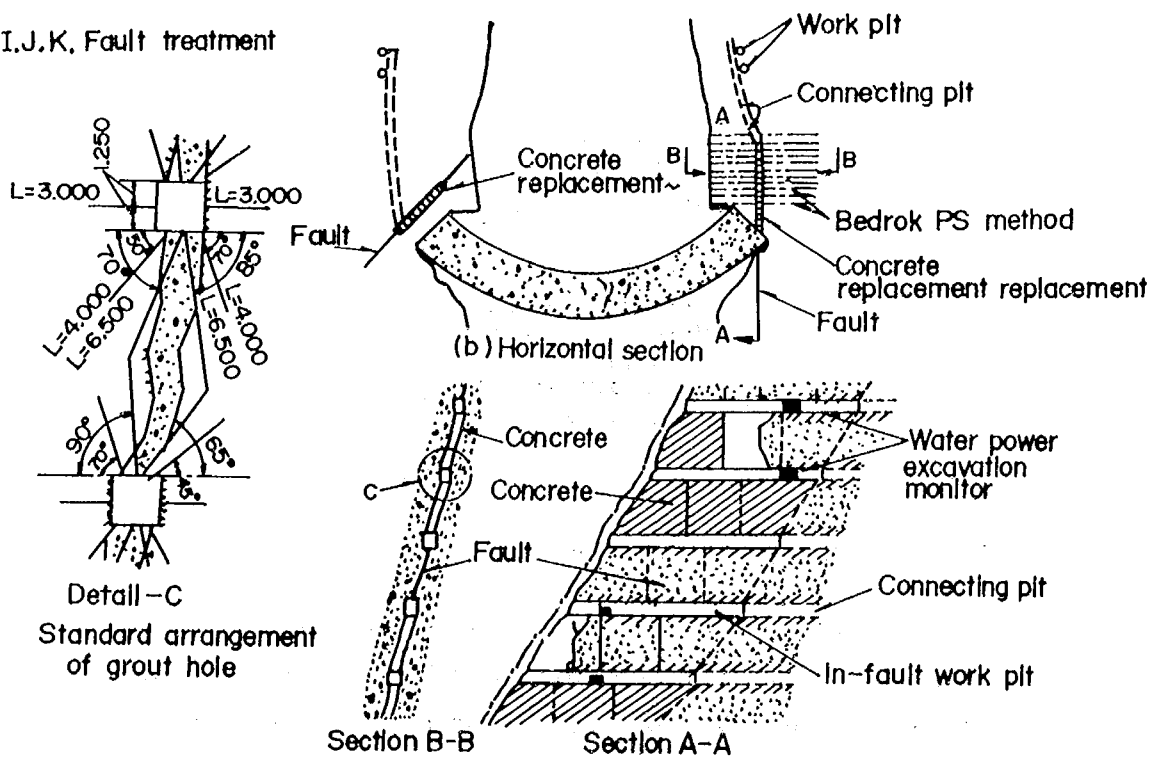


Fig. 17 Fault treatment at Nagawado Dam

3. SPECIAL FOUNDATION TREATMENT METHODS

Under foundation grouting the permeability and deformability of the bedrock can be improved as far as the ordinary hard rock is concerned. However, it is generally believed that the bedrock strength cannot be improved. Also, there are cases where it is not economical to improve the permeability and deformability by grouting. In such cases, special foundation treatment methods are employed to improve the conditions of the dam foundation bedrock to enhance the safety factors of the dam. These methods are broadly classified into the followings:

- (1) To replace brittle zones with concrete where problems in strength and deformability exist.
- (2) To stop water seepage by using plugs or continuous cut-off walls at points where it is difficult to check water by grouting.
- (3) To bind foundation bedrock with steel materials to mainly check deformability.

3.1 Concrete Replacement of Brittle Zones

Concrete replacement methods are most often employed in Japan mainly for the arch dam.

The brittle zone represented by fault shattered zones in the bedrock has lesser strength, higher deformability, in comparison with the surrounding hard rock, and is easily deteriorated by water seepage. Such zones are replaced with concrete. With precise execution, we can determine the brittle zones are replaced with concrete.

Examples of typical executions are given below.

(1) Concrete-replacement treatment at Kurobe IV Dam

The Kurobe No.4 Arch Dam is 176 meters high, the highest in Japan. The brittle IV Arch Dam is 176 meters high, the highest in Japan. abutment was detected. The brittle zone was replaced at the upper left bank, with about 40,000 cubic meters of concrete to prevent the excessive deformation in the abutment.

A critical item is where looseness occurs during excavation of the bedrock and the fault. If the surrounding bedrock were to become loosened, the deformability increases and the strength lowers, thus reducing the effect of fault replacement by one-fault. Consequently, an excavation method using jet water was employed at the Nagawado Dam. The jet water pressure was 100 to 200 kg/cm².

(3) Transmitting wall at the Kawamata Dam.

Although this is different from the replacement of the brittle zone, the transmitting wall of the Kawamata Dam is also one kind of concrete-replacement methods project. At the Kawamata Dam (arch, H=117 m), in order to prevent the dam thrust from working on the fault, the concrete transmitting wall was created inside the bedrock (Figure 18).

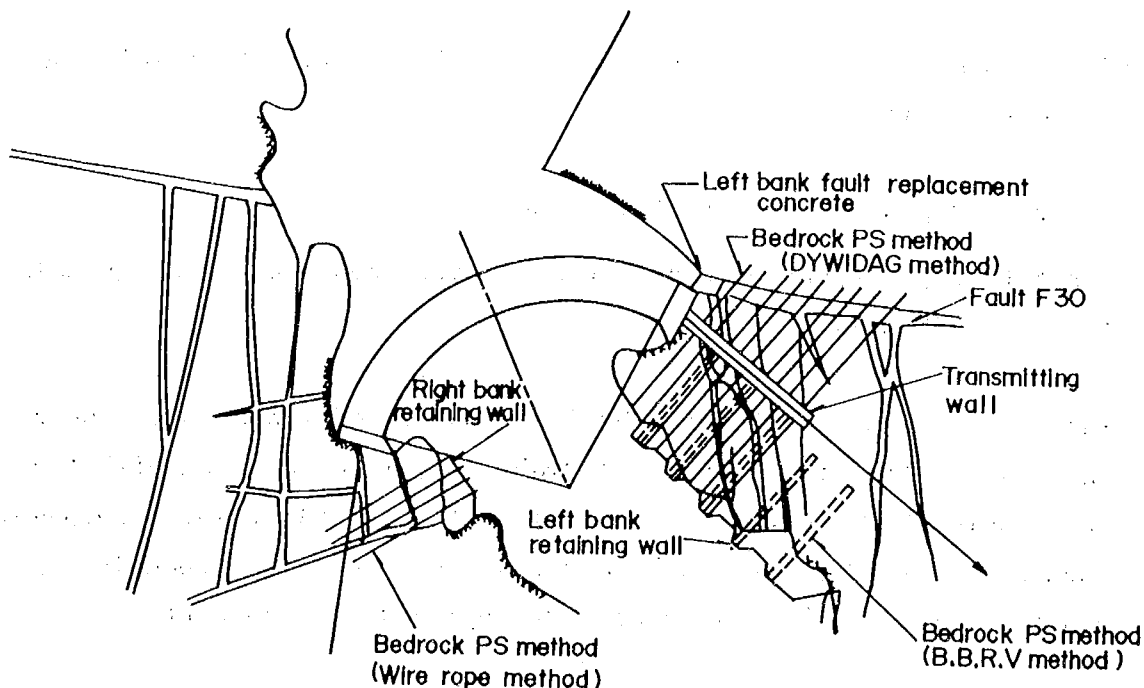


Fig. 18 Transmitting wall at Kawamata Dam

Taking advantage of the difference in deformability between the bedrock and concrete, most of the load was transmitted down to the deepest section of the bedrock.

This was done by digging a tunnel and filling it with concrete and repeating the process many times.

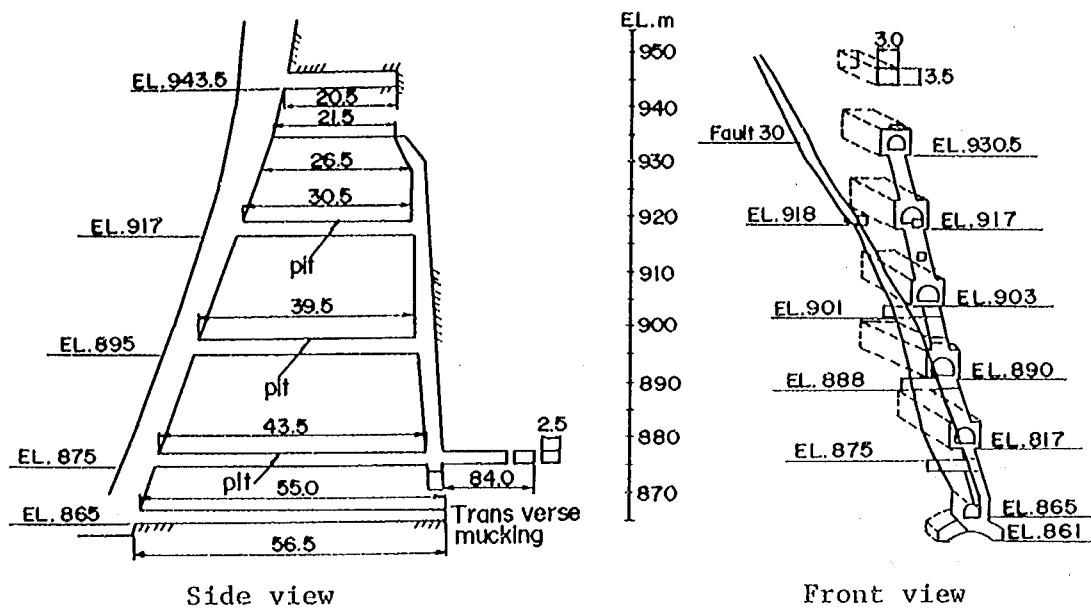


Fig. 19 Creation of the transmitting wall

3.2 Cut-off Plug and Continuous Cut-off Wall

Where there is a brittle zone, such as a fault near the upstream section of the dam, or fault line in the up and downstream direction at the dam foundation, the concrete plug is provided at the upstream end of the dam.

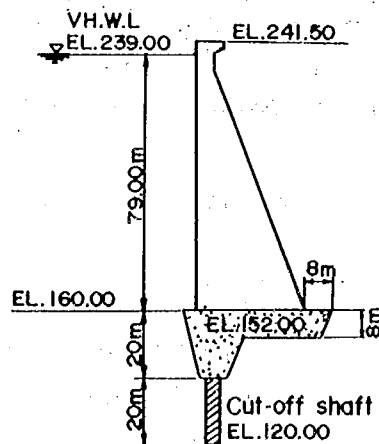


Fig. 20 Cut-off plug at Yuda Dam

There are also cases where gravel layers in the foundation are located at considerable depth and it is not economical to remove layers by excavation. Furthermore, these gravel layers and a certain kind of the bedrock make cement grouting very difficult or expensive.

In such a case, a continuous cut-off wall is used to stop water seepage. This is done by excavating bore holes with the percussion, then inserting concrete or asphalt concrete. By repeating this process, a continuous cut-off wall is constructed.

At the Yagisawa Dam (arch, H-127 m), there was a gravel layer beside the main river that was suspected as the accretion layer of the old riverbed. Since it was not considered a good idea to construct a dam after removal of the layer by excavation, a fill dam was directly constructed on this gravel layer, and the foundation cut-off was made by creating continuous cut-off walls of concrete through the ICOS method.

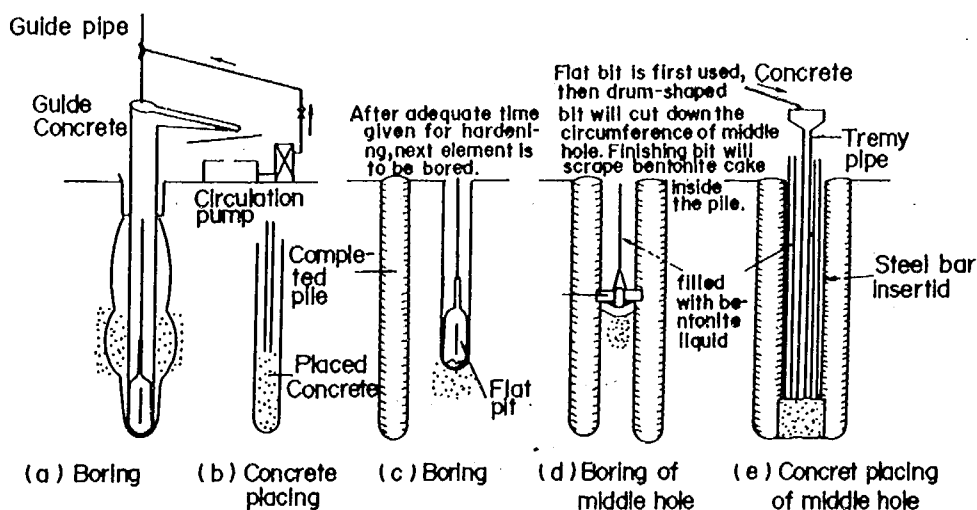


Fig. 21 ICOS method (Yagisawa Dam)

3.3 Bedrock PS Method using Steel Bars

Foundation bedrock, even in a comparatively uniform condition, and close to an elastic body, is generally deformed when loaded with the dam, bulging toward the gorge. Deformation is aggravated where the foundation bedrock has fault lines, seams and joints in advanced deteriorated conditions, which are likely, in an extreme case, to cause loosening of the foundation bedrock, decrease load-durability, and lead to its collapse. To restrain the bulging load-deformation and to consolidate the foundation bedrock, the bedrock PS method is used.

This method is done by first excavating the bedrock to the design depth. Steel materials such as steel bars, steel wire, etc. are then inserted and fixed at an end to the bedrock. Steel materials can be tightened as required for prestressing the bedrock. Arrangement of the steel material and scope of the prestressing work are determined after considering the geologic conditions of the bedrock, stress distributions, the deformability, etc. However, it is commonly understood that the prestressing amount supplied to the bedrock cannot be excessive in relation to the working stress from the dam, since the latter force is tremendous in and spans a wide area. Therefore, although prestressing of the dam foundation is effectively employed as a preventive measure against local tensile stress, it is difficult to improve the stress condition of a wider foundation area. This is one reason why this method is employed together with the fault-replacement method, and is regarded as effective in solving the loosened bedrock at construction.

This method was employed in Japan at the Kawamata Dam, Nagawado Dam, Kawaji Dam, etc. The bedrock PS method at the Kawamata Dam is shown in Figure 22 (also see Figure 18).

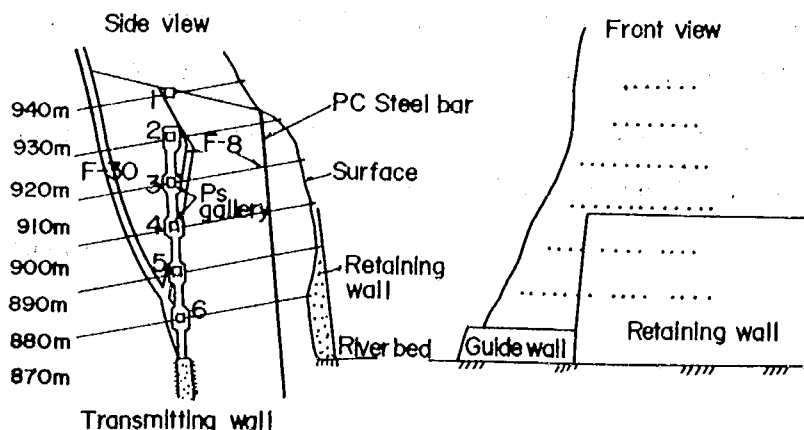


Fig. 22 Bedrock PS Work (Kawamata Dam)

The effects of the bedrock PS method can be explained by Mohr's stress circle as shown in Figure 23.

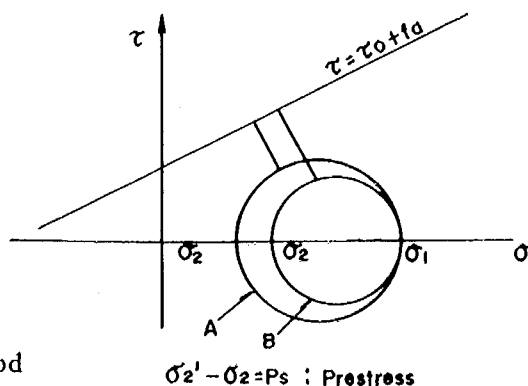


Fig. 23 Effects of bedrock PS method

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**Foundation Treatments
for Dams**

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Mitsuaki Mizuno

Nario Yasuda

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Grouting Consolidation Grouting Lugeon Value

Summary

This paper presents foundation treatments for dams contained concrete gravity dams, arch dams and fill type dams, and it explains foundation grouting (curtain grouting, consolidation grouting and blanket grouting) and special foundation treatment methods (concrete replacement, cut-off plug and continuous cut-off wall, rock PS method).

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